ON THE FAILURE MECHANISM OF MASONRY SUBJECTED TO COMPRESSION
- ZUM BRUCHMECHANISMUS VON MAUERWERK BEI DRUCKBEANSPRUCHUNG -

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ABSTRACT It is known that the failure mechanism of masonry subjected to compression is governed by the deformation characteristics of the units and the mortar in the direction perpendicular to the applied forces. Not known, however, is the numerical relationship between the masonry strength and the deformation characteristics. In this contribution a corresponding equation is developed. For the time being the equation is especially applicable for masonry erected with leight mortar in order to decrease the thermal conductivity.

Es ist bekannt, daß bei auf Druck beanspruchtem Mauerwerk der Bruchmechanismus durch die Verformungseigenschaften der Steine und der Mörtel bestimmt ist. Nicht bekannt ist jedoch der zahlenmäßige Zusammenhang zwischen der Mauerwerksfestigkeit und den Verformungseigenschaften. Im vorliegenden Beitrag wird eine entsprechende Gleichung angegeben. Sie ist zur Zeit in erster Linie für Mauerwerk mit Leichtmörtel, der zur Herabsetzung der Wärmeleitfähigkeit verwendet wird, anwendbar.

1. INTRODUCTION

We usually assume that there is a relationship between the compressive strength of masonry and the compressive strengths of the used units and mortars. We, however, on the other hand know that in testing a wall we get cracks in the same direction like the applied forces. This means that by the acting vertical forces horizontal tensile forces must be produced. They obviously become higher than the tensile strength of the units so that the cracks occur. In other words not the compressive strength but the tensile strength of the units is a decisive value for the masonry strength. For this there is an explanation: In applying vertical forces we do not only get deformations in the vertical direction but also in the horizontal direction. If we now assume that the horizontal deformations of the units and the mortar are different and if especially those of the mortar are higher than of the units we get tensile forces in the units perpendicular to the applied vertical forces. This means, that the difference of the lateral deformations of the units and the mortar is of great influence on the bearing capacity of a wall. In other words the masonry strength f_m should be described by a function of the lateral deformation characteristics of the units and the mortars. The deformation characteristics might be the modulus of elasticity in the lateral direction:

$$f_m = f_{(E_{1,u}, E_{1,mo})} \qquad (1)$$

(f_m = masonry strength, $E_{l,u}$ = modulus of elasticity in the lateral direction of the units, $E_{l,mo}$ = modulus of elasticity in the lateral direction of the mortars).

The above considerations are not new. They also have been verified by calculations using the method of finite elements (1). Not known, however, are investigations on the numerical relationship between f_m, $E_{l,u}$ and $E_{l,mo}$. Corresponding tests have been carried out in Germany during the last years. On the results will be reported in this contribution.

2. TESTS

2.1 General

If the masonry strength is a function of the modulus of elasticity in lateral direction of the units and the mortar the question arises why e.g. in our standards we are able to describe the masonry strength by means of the compressive strengths of the units and the mortar. The answer is simple: As long as the compressive strengths are in relation to the modulus of elasticity in the lateral direction - or more general in relation to the deformation characteristics - there are of course relationships between the compressive strengths. And obviously it is, that for the usually used units and types of mortar the required relation exists. This means that also in future there is no need to change the relationships in our codes. There might, however, be cases where we have to handle the problem in a different way. One of those cases is the application of leight material as aggregate for the mortar in order to decrease the thermal conductivity. In alarming tests (2) several years ago it was found that using a certain sort of leight material as aggregate for the mortar the masonry strength was about 30 % of that strength if normal sand as aggregate was used though both mortar strengths were the same. Because since the energy crisis the application of leight mortar became very common in Germany it was necessary to go more in detail. Basis of the experiments became the ideas which are behind equation 1. Besides of the practical use of the required tests it was an excellent opportunity to get more numerical information for equation 1 and by this another verification for the validity of the theory on the failure mechanism of masonry.

2.2 Testing Programs

Because the use of leight mortar was not indroduced overnight but step by step several test programs were carried out in several laboratories. In all tests the following dates have been determined:

Mortar: compressive strength, stress-strain-relationship in vertical and horizontal direction.

Units: like mortar.

Masonry: wall strength.

The used mortar was cement-lime-mortar with different kinds of aggregates: natural sand (for comparison), expanded clay, expanded shale, pumice and perlite. For some mortars air entraining agents were used so that partly up to 20 % air pores were introduced to the mortar.

The units were perforated clay bricks, calcium silicate cellular blocks, leighweight concrete solid bricks and cellular blocks and aerated concrete blocks.

2.3 Test Results

Within the frame of this paper the test results cannot be given in detail. They are collected (about results of 120 wall tests and accompanying units and mortar tests) in (3).

2.4 Evaluation of Test Results

2.4.1 Deformation Characteristic of the Mortar

As said in clause 2.2 the stress-strain-relationship of the mortars in the vertical and the horizontal direction have been determined. From these stress-strain-relationships were the modulus of elasticity in both directions calculated. They were defined as secant modulus at 1/3 of the mortar strength. It was assumed that these figures are characterizing values for the deformation behaviour of a mortar.

2.4.2 Deformation Characteristic of the Units

The stress-strain-relationships of the units were also determined. Like in the case of the mortar also for the units the secant modulus of elasticity at 1/3 of the unit strength was defined and considered to be the characterizing values.

2.4.3 Relationships between the Masonry Strength and the Modulus of Elasticity of the Units and the Mortar

At first it was tried to find a relationship between the masonry strength f_m, the modulus of elasticity in lateral direction of the units $E_{l,u}$ and the modulus of elasticity in lateral direction of the mortar $E_{l,mo}$. The chosen equation was of the following type:

$$f_m = a\ E_{l,u}^{b} \cdot E_{l,mo}^{c} \qquad (2)$$

In equation a, b and c are coefficients. They were determined using the method of least squares. They became: a = 0,32, b = 0,44 and c = 0,29.
(Dimensions: f_m, $E_{l,u}$ and $E_{l,mo}$ in N/mm², for the numerical evaluation divide the values $E_{l,u}$ and $E_{l,mo}$ by 1000 and give these figures in the equation).

The comparison between the masonry strength calculated using equation 2 with the above mentioned figures for a, b and c and the corresponding strength from the test results showed that there were partly very high deviations. Only half of the test results differend not more than ± 20 % from the calculated values. The mean standard deviation was 1,29 N/mm². Both deviations were thought to be too high.

Going through the test results for the determination of $E_{l,u}$ and $E_{l,mo}$ it was found, that they differed in a wide range. The mean coefficient of variation for $E_{l,mo}$ was 9,2 %. The mean coefficient of variation for $E_{v,mo}$ (modulus of elasticity in the vertical direction of the mortar that is to say the usually determined modulus of elasticity), however, it was only 3,8 %. The difference was explainable: The deformations in the lateral direction are much smaller than those in the vertical direction. This means that the error in measurement in the laterial direction is accordingly higher than that in the vertical direction. Besides of this it was seen that there is a correlation between the modulus of elasticity in the laterial direction and the modulus of elasticity in the vertical direction. Therefore it could be expected that there is also a relation between the modulus of elasticity of the units and the mortar in vertical direction and the masonry strength. In order to check this an equation similar to equation 2 was chosen. The coefficients a, b and c have been again determined by using the method of least squares. The result was:

$$f_m = 0,98 \cdot E_{v,u}^{0,56} \cdot E_{v,mo}^{0,26} \qquad (3)$$

The mean standard deviation was 1,0 N/mm² and nearly 60 % of the calculated masonry strength from equation 3 differed not more than ± 20 % from the test results. So there was an improvement in comparison with the first trial when the modulus of elasticity in the lateral direction were used.

A further evaluation of the test results showed, that there is a relationship between the modulus of elasticity in the vertical direction of the units $E_{v,u}$ and their compressive strength f_b. The relationship was found with

$$E_{v,u} = 0,98 \cdot f_b^{0,77} \qquad (4)$$

A similar investigation on the relationship between modulus of elasticity in the vertical direction of the mortar $E_{v,mo}$ and the compressive strength of the mortar indicated that between these values was not a similar clear relationship like with the units. It could, however, be seen that there were groups and that the modulus of elasticity mainly depended on the typ of aggregate in the mortar. For each type of mortar was the modulus of elasticity a certain value which did not depend on the compressive strength of the mortar. It therefore became also understandable, that the compressive strength of the mortar cannot be used as a characterizing value for the masonry strength. It verified the considerations according to which the compressive strength of the units and the mortar for a relation to the masonry strength can only be used if these values correlate to the modulus of elasticity.

Equation 3 may be used to calculate the masonry strength. Using equation 4 $E_{v,u}$ in equation (3) may be replaced by the more common value f_b, the unit compressive strength. We obtain

$$f_m = 0,97\ f_b^{0,43} \cdot E_{v,mo}^{0,26} \qquad (5)$$

Equation 5 may be considered to be a relationship which considers the failure mechanism of masonry. This is a scientific step forward and makes us more confident in our knowledge on masonry and its behaviour. One point, however, has to be mentioned. Most of the values for the determination of the coefficients a, b and c where found from masonry tests with rather a low strength. This means that the range within which the equation 5 may be applied is rather small. For the time being further tests are carried out to make the equation more reliable.

3. SUMMARY

In order to check our ideas on the failure mechanism of masonry tests have been carried out in which the deformation characteristics of the units and the mortar were determined. In the evaluation of the test results it was found, that there is a relationship between the masonry strength and the modulus of elasticity in the laterial direction of the units and the mortar. Therefore our conception on the failure mechanism has been verified. Further more it is shown that instead of the modulus of elasticity in the lateral direction in case of the units their compressive strength may be introduced while in case of the mortar the corresponding value may be replaced by the modulus of elasticity in the vertical direction.

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